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STUDY OF FLIGHT ENVIRONMENT EFFECTS ON HELICOPTER GUNNER

Carl Larson, et al

Army Aeromedical Research Laboratory
Fort Rucker, Alabama

June 1973

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USAARL REPORT NO. 73-15

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By

Carl Larson, Ph.D.
Edward Wells, M.S.
Drexel University
Philadelphia, Pennsylvania 19104

And

LTC Burton H. Kaplan, M.D.
U. S. Army Aeromedical Research Laboratory

June 1973

U. S. ARMY AEROMEDICAL RESEARCH LABORATORY

Fort Rucker, Alabama 36360

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ABSTRACT

Disorientation periods of a helicopter gunner in the conduct of his task during a planned flight profile were investigated through the use of a computerized mathematical model of the vestibular system. Flight attitude and crewman seat change data were used as input to the model and crewman nystagmus rates and perceived angular sensations were predicted. These output data were then compared to actual onboard flight observations of crewman status and well being. The mathematical model was found to accurately predict periods of disorientation that coincided with those observed and were manifested by either excess nystagmus rates, perceived sensations of motion, or a combination of both. Rapid changes in seat angle were attributed as the primary cause of disorientation with vehicle attitude changes cross-coupled with seat angle changes, producing a secondary effect.

APPROVED: ROBERT W. BAILEY
Colonel, MSC
Commanding

STUDY OF FLIGHT ENVIRONMENT EFFECTS ON HELICOPTER GUNNER

INTRODUCTION

Human spatial orientation is dependent on intricate central nervous system integration of sensory information derived from vestibular, visual, auditory, and proprioceptive receptors, the latter receptors being primarily located in the muscles and joints. During prolonged exposure to unusual or stressful environmental conditions, the function of one or more of these receptor mechanisms may be altered, thereby leading to potentially significant disruptions in spatial orientation and performance. Spatial disorientation and related performance degradation can also be produced by conflicting sensory cues. The central nervous system is believed to be able to cope with such sensory conflicts and alterations in receptor function by filtering or inhibiting spurious sensory information while placing greater emphasis on the processing of sensory information from other modalities. Specific conditions by which each of the sensory mechanisms is affected, the manner in which the sensory systems interact, and the overall capability of the central nervous system to compensate for altered sensory information are not well understood.

Disorientation is related to visual stimulation. Man is a vertebrate organism that has evolved a powerful set of interlocking hierarchial control mechanisms for stabilization of the visual image on the retina of the eye. As mentioned before, the major sources of efferent information of these reflex controls are vestibular, visual, auditory, and proprioceptive. On the efferent side of the reflex arc, visual stabilization is achieved through compensatory and tracking movements of the eyes and head and, to a lesser extent, through adjustments of body position and posture. The subsystems involved in control of these three effector platforms are closely related; they use sensory information that arises in many cases from the same sources and share many neural transmission and processing facilities. In addition, these systems are all to some extent involved in posture adjustment and in the subjective awareness of body orientation and of the disposition of body parts--a fact that further emphasizes their close functional relationships. From the above discussion, the complexity of the disorientation problem is evidenced. Also, it is apparent that it would be impossible to study all aspects of a human body's reactions to a stressful environment. Therefore, for this investigation of a helicopter crewman subjected to rapid angular acceleration changes in the performance of his task, resulting vestibular system responses were studied, because they will cause the most detrimental effects on a crewman's performance.

A mathematical model of the vestibular system was developed and utilized in this investigation. In developing the model, anatomical and neurophysiological data were used to identify vector transformation matrices that predict how the inputs and outputs of the sensors in the same anatomical plane add their responses for a given input acceleration. As a result this model allows the application of simple and complex angular accelerations to the body and obtains the resultant effects through the use of the vestibulo-ocular reflex arc, a very sensitive measurement of vestibular stimulation.

The sensors themselves were modeled after control system function techniques primarily developed in the past decade. The basic transfer function schemes were based on much experimental data and were therefore used per se, except where it was advantageous to obtain a better fit to experimental data.

The outputs of the program consist of nystagmus and perceived angular acceleration due to the semicircular canal outputs. It was felt that, with these outputs, it would be possible to make some simultaneous comparisons between what the crewman sees and what he perceives as a result of a specific angular acceleration. The analysis section of this report attempts to accomplish this goal.

VESTIBULAR SYSTEM

The vestibular system comprises one set of important sensors used by man to control his posture, direct his gaze, and construct his subjective perception of orientation in space. The basic components of this system are linear and angular accelerometers, called otoliths, and semicircular canals. The otoliths are calcium carbonate concentrations which are embedded in gelatinous material and rest on sensory cells in the fluid filled chambers, called the utricle and saccule. The semicircular canals are liquid filled loops[1 2 3] arranged in three orthogonal planes, and in each loop is a swelling, the ampulla, containing a hinged gelatinous valve, the cupula. Supported on sensory hair cells, the cupula transduces angular acceleration movements of the fluid into neural signals. Details of this sytem are snown in Figure 1.

Stimulation of the vestibular system can be caused by acceleration inputs from the imposed environment itself or by combinations of head movements independent or superimposed on the environment. As a result, abnormal responses can be produced under certain conditions. Effects to the crewman may consist not only of deficiencies in sensory-motor

coordination, but also in various illusions due to "cross-modality" interactions.[4] Primarily, the illusions experienced involve error in interpreting the visual environment relative to that perceived. The following is a brief description of illusions resulting from angular accelerations.

Oculogyral Illusion - The oculogyral illusion (OGI) results when the latency threshold of the semicircular canals has been exceeded by an increase or decrease in angular acceleration of the helicopter in its attitude changes or by rotation of the seat. This can occur without head movement; it is caused by a reflex response (nystagmus) consisting of movements of the eyeball following semicircular canal stimulation[5 6 7] by the physical environment. The direction of apparent motion is in accord with the sensation of rotation during acceleration. If the subject is rotated to the right, a visual target fixed in relation to the subject appears to move in that direction. Movement gradually comes to a standstill, after which it may appear to shift slowly to the left. When rotation is stabilized or angular velocity is a constant, apparent motion ceases. Sudden deceleration causes the visual target to have rapid apparent motion to the left, with a successive stage in which apparent motion is to the right. This reflex response of the eyeballs cannot be eliminated, and the only remedy is to train the crewman to ignor the sensations it produces.

The threshold of the OGI is approximately 0.2 to 0.3°/sec^2; however, reported threshold values in the literature vary from 0.35°/sec^2 to 2.0°/sec^2. OGI has been studied in human subjects with real targets, after images, and simultaneous presentation of the two. It seems that the apparent movement is associated with efferent activity in the agonist to the slow phase efferent activity present as a result of labyrinthine stimulus. The magnitude of the oculogyral illusion varies in relation to the rate of angular acceleration, position of the head, illumination of the target and background, and the experience of the individual.

Coriolis Illusion - The coriolis illusion results primarily from a cross-coupling of the simultaneous rotations in two semicircular canals, in this case, caused by the helicopter and rotating seat. The illusion that results is a rotation that appears about an axis which is perpendicular to the two input angular accelerations. The effect of this illusion usually causes a crewman to suffer a severe loss of equilibrium[8-11] and possibly extreme dizziness and nausea. Training by repeated exposure to the coriolis effect can produce resistance to the illusion.[10 12] Both the oculogyral illusion and the coriolis illusion are manifested by nystagmus and perceived rotation, except the latter, in general, has a more complex and bizarre resultant effect.

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VESTIBULAR SYSTEM DYNAMIC MODEL

Model Flow Diagram - Figure 2 presents an overall block diagram describing the flow of the computerized vestibular system math model. First, the helicopter flight attitude parameters and rotating seat attitude are differentiated twice to obtain angular acceleration terms (Part A). These terms are the input accelerations and are vector transformed in Part B into the crewman's head coordinate system. The resulting components are next vector transformed (Part C) into the anatomical planes of the semicircular canals. Anatomical details of where these sensors are located in the head and other pertinent assumptions regarding the action of the sensors will be presented in subsequent sections.

The dynamics of the sensors are next modeled in Part D. Included in this part of the model are sensor thresholds, adaption terms, and neural delays, where appropriate. At this time, the model does not attempt to include any cross-coupling of information between sensors but treats them as independent linear systems. A vector transformation of the sensor outputs back into the head coordinate system is included (Part E) to place the resulting sensor actions (eye movements, etc.) in cognizance with normal subjective (perceived) and objective (experimental) results. In essence, an individual relates the perceived and visual effects of an input acceleration environment in terms of the coordinate system in which he exists.

Transformation into Head Coordinate System - Normally, the crewman is oriented in the helicopter such that his roll, pitch, and yaw axes coincide with those of the helicopter. Movement of his head from this zero position is then tracked through the use of Eulerian angles. The following Eulerian angle matrix transformation sequence is used to transform the input accelerations into the moving head coordinate system (x", y", z").

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \text{xheado} \\ \text{yheado} \\ \text{zheado} \end{bmatrix}$$

$$\begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

Finally,

$$\begin{bmatrix} \text{WHEAD X} \\ \text{WHEAD Y} \\ \text{WHEAD Z} \end{bmatrix} = \begin{bmatrix} \cos\psi & 0 & -\sin\psi \\ 0 & 1 & 0 \\ \sin\psi & 0 & \cos\psi \end{bmatrix} \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix}$$

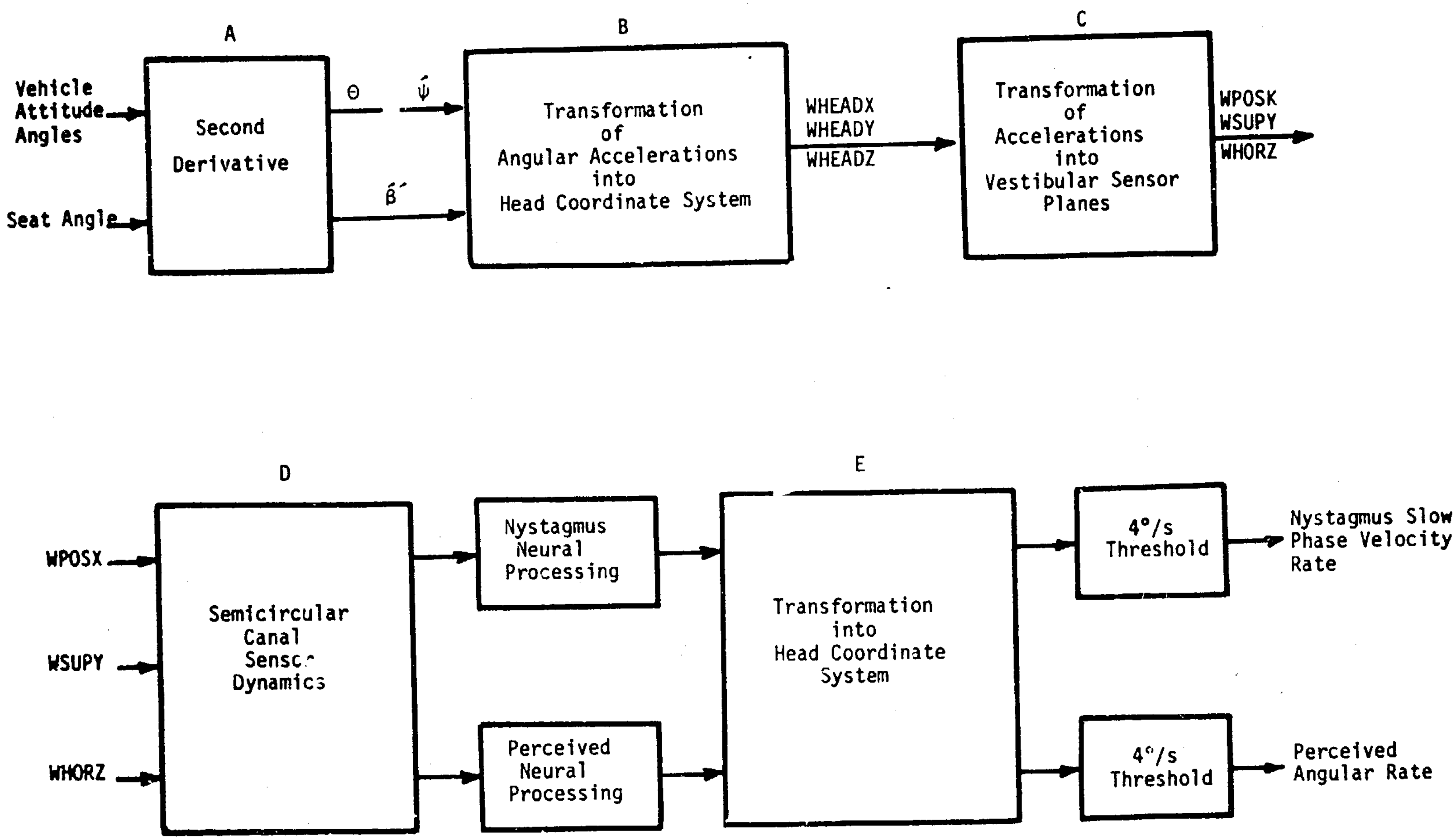

FIGURE 2. Composite Vestibular System Math Model Flow Diagram

It should be noted that the sequence followed in this program was yaw (α), roll (β), and then pitch (ψ). Selection of a different sequence would, of course, yield different resulting equations.

Transformation of Accelerations into Sensor Planes - The semicircular canals are described above as liquid filled loops arranged in orthogonal planes, and in each loop is a swelling--the ampulla--containing a hinged gelatinous valve--the cupula. The cupula is responsible for changing mechanical energy (fluid motion) into neural signals proportional to the input energy. Stereocilia and kinocilium play a part in this transformation. Neurophysiology shows that in the horizontal canal cristae, all kinocilium are oriented toward the utricle, whereas in the vertical canals they are oriented away from the utricle. This implies that the acceleration relationships expressed in vector form for the two sets of canals are as shown in Figure 3.

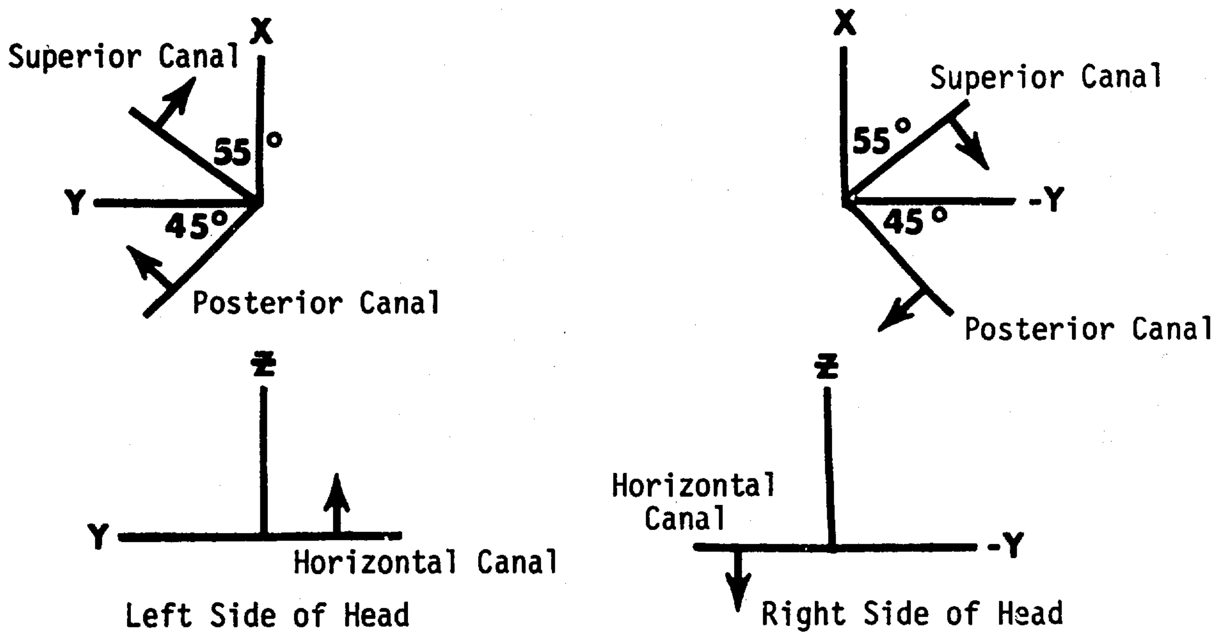

FIGURE 3. Positive Angular Acceleration Stimulus in Vector Form for the Semicircular Canals

It is observed in all cases that an angular acceleration input to the head causes an equal and opposite vector output from the pairs of canals oriented in the same reaction plane. Each semicircular canal is, hence, sensitive to a specific angular acceleration vector input. Also,

it is noted that the canals in the same reaction planes on the opposite sides of the head have opposite vector responses to a given input. Electrophysiological data,[11] however, can be used to give a possible answer to how these canals add to yield direction and magnitude information to the brain. It is concluded from research data that it is possible to sum (electrically) any two canals in a given reaction plane and obtain output magnitude and direction information to feed to the brain. Since the transformation equations are vector transformations, this corresponds to a subtraction of vectors to achieve an addition of potentials. The equations sum the canals in the same reaction planes such that two horizontal canals and the corresponding superior-posterior canal pairs yield one resulting right-hand set of vector equations. In addition to the angular information shown in Figure 3, the horizontal canals are also known to be located approximately in the same plane as the utricle macula (-30° in the XZ plane). The following transformation equations result:

$$\begin{aligned} \mathrm{WPOSX} = {} & \mathrm{WHEADX} \cos 30 \, (\cos 45 + \sin 55 \sin 10 + \cos 10) \\ & + \mathrm{WHEADY} \, (\sin 45 + \cos 55 \cos 10 - \cos 55 \sin 10) \\ & + \mathrm{WHEADZ} \sin 30 \, (\cos 45 + \sin 55 \cos 10 + \sin 55 \sin 10) \end{aligned}$$

$$\begin{aligned} \mathrm{WSUPY} = {} & - \mathrm{WHEADX} \cos 30 \, (\cos 45 + \sin 55 \sin 10 + \sin 55 \cos 10) \\ & + \mathrm{WHEADY} \, (\sin 45 + \cos 55 \cos 10 - \cos 55 \sin 10) \\ & - \mathrm{WHEADZ} \sin 30 \, (\cos 45 + \sin 55 \cos 10 + \sin 55 \sin 10) \end{aligned}$$

$$\mathrm{WHORZ} = 2 \, (-\mathrm{WHEADX} \sin 30 + \mathrm{WHEADZ} \cos 30)$$

Semicircular Canal Neural Processing Model - The basic transfer function models describing cupula movement for angular acceleration input used in this math model are as shown in Figure 4.

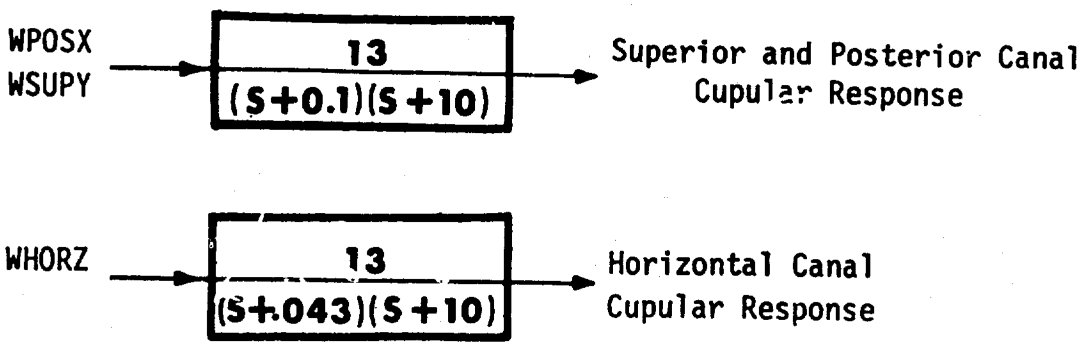

FIGURE 4. Semicircular Canal Sensor Dynamic Models

The pole of 10 (short time constant of 0.1) which describes the fast rise time of the cupula response for an impulse angular acceleration input was retained from the literature.[12, 13] The long time constant and the gains of the transfer functions will both be discussed in a later section.

The desired outputs are perceived angular acceleration and nystagmus. The models developed by Meiry were, therefore, modified according to Young,[13] who introduced a 125 sec adaptation term for nystagmus and a 30 sec adaptation term for perceived angular acceleration. It was also felt that both nystagmus and perceived acceleration are derivatives of cupular angular movement. Figure 5 presents these modifications to the semicircular canal model.

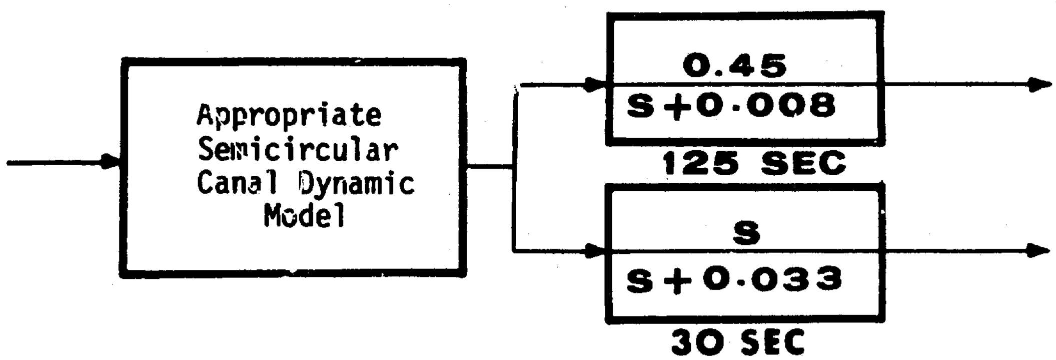

FIGURE 5. Total Semicircular Canal Models Including Nystagmus and Perceived Angular Acceleration

Semicircular Canal Sensor Output Transformation - The transformation equations for the semicircular canal outputs into the head coordinate systems are as follows:

WHDPX = 0.2 (WPOSX COS 45 cos 30 - WSUPY sin 45 cos 30 - WHORZ sin 30)
WHDPY = WPOSX sin 45 + WSUPY cos 45

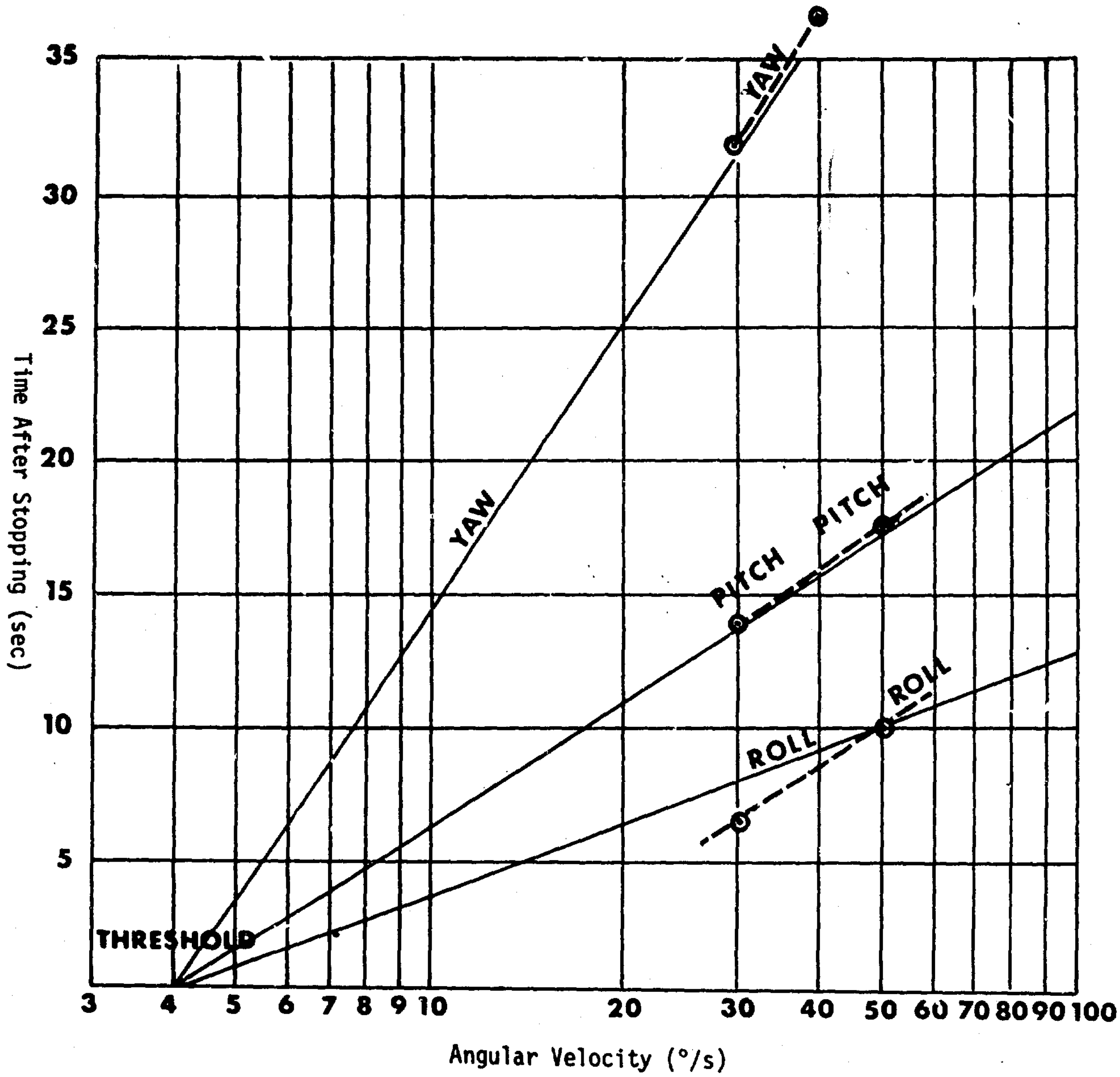

FIGURE 6. Objective Cupulometry for the Semicircular Canals

WHDPZ = WPOSX cos 45 sin 30 - WSUPY sin 45 sin 30 + WHORZ cos 30

The 0.2 that is a multiplying factor in the first equation will be explained in Nystagmus Calculation Section. The same equations are used for both nystagmus and perceived angular accelerations.

Nystagmus Calculations - Above, it was mentioned that the gain and value of the selected long time constant of the semicircular canal transfer functions would be discussed later in this report. Objective cupulometry data from the literature[14] yield the curves given in Figure 6. The slope of each line gives the objective mean time constant obtained for pitch, yaw, and roll accelerations. Each time value on the curve is obtained by spinning the man at a selected constant angular velocity and then stopping him quickly (so as to obtain an acceleration impulse) and observing the time required for nystagmus to cease. The gain and pole values in the transfer functions were then determined such that the results would fit the curves. The points shown in Figure 6 for pitch, yaw, and roll at 30°/sec and 50°/sec represent the responses of the systems with the selected gains and poles. It is noted that the roll response is not an accurate fit, but it is the best possible fit with the vector transformations and canal summing technique utilized in this program. The 0.2 multiplying factor used in the sensor output transformation equation was also required to be introduced into the equation in order to obtain this degree of fit. At present, the response over a 30°/sec - 90°/sec range is accurate with ±15%.

A 4°/sec threshold is included in the overall system describing nystagmus rate as shown in Figure 7.

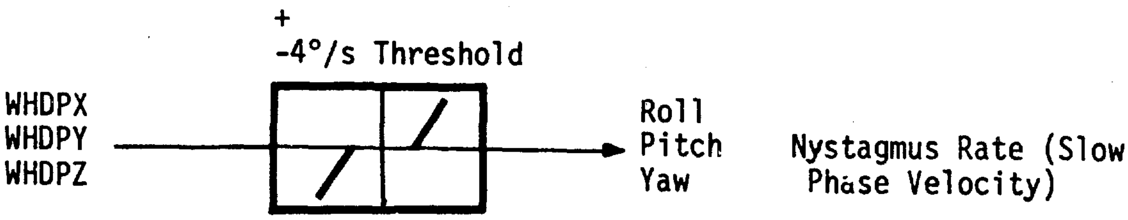

FIGURE 7. Calculation of Nystagmus Rate

Perceived Angular Velocity Rate Calculations - The perceived acceleration adaptation term (30 seconds) shown in Figure 5 was taken from Reference 14, and no attempt was made in this program to modify it to fit

the curves plotted in Figure 9. A comparison of the results of this program with those published in Reference 14 shows that the mean time constant for yaw and pitch are not correct, while roll is approximately correct. It is suspected that the CNS adaptation term as shown by Young[13] needs to be lengthened and the gain of the term modified. This system also includes a 4°/sec threshold as shown in Figure 8.

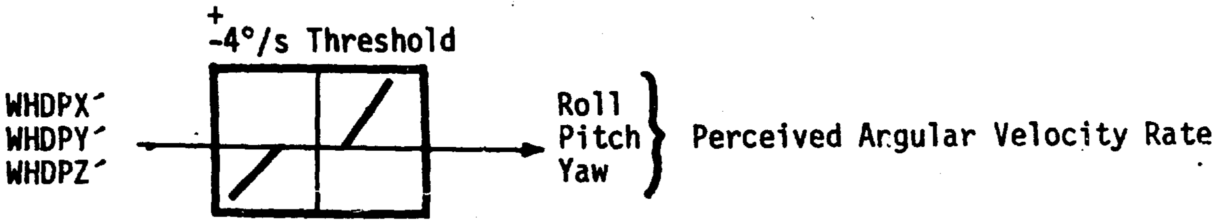

FIGURE 8. Calculation of Perceived Angular Velocity Rate

FLIGHT PROFILE ANALYZED

General - The flight profile analysis consists of three parts: (1) Analysis of the effects due to the seat alone; (2) Analysis of the effects due to the helicopter alone; and (3) Analysis of the effects due to the combination. In all these cases the crewman was oriented initially aligned with the helicopter axes but with head tilted 45° forward. This forward angle was the normal attitude he would assume in the conduct of his task. The flight profile (Figure 10) provided the input conditions for the computer program and consisted of helicopter roll, pitch, and heading (yaw) angles versus time, and seat angle versus time. The profile duration was 330 seconds of elapsed time.

For the analysis, Figure 11, A,B,C,D,E,F,G conditions (on board observations of crewman performance decrements) were compared to the math model predicted results. It should be noted that in the actual flight profile, the crewman did not keep his head tilted 45° forward during the entire mission; therefore, obvious differences between the actual and predicted will occur for these periods.

The procedure used in each computer run was first, to insert the

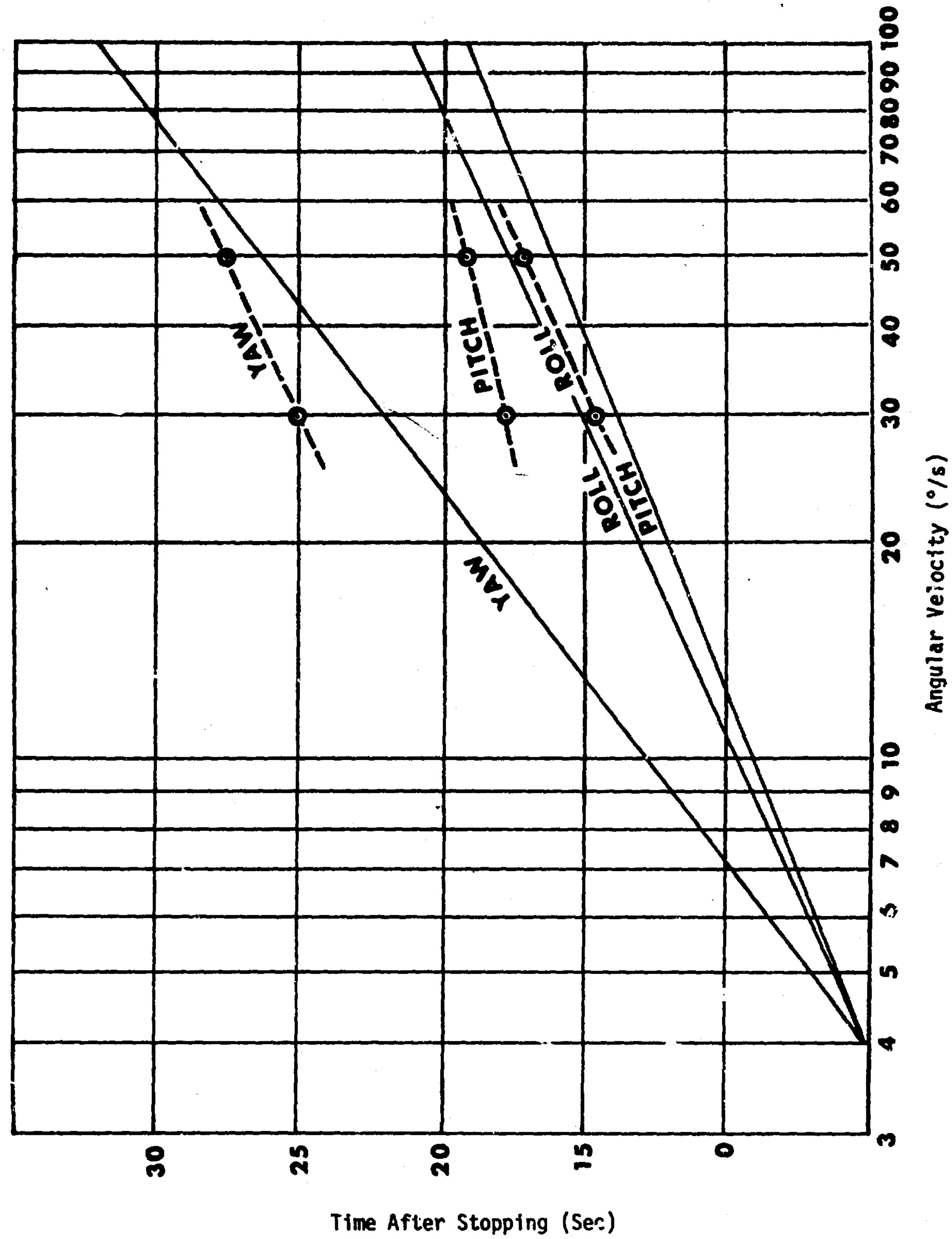

FIGURE 9. Subjective Cupulometry for the Semicircular Canals

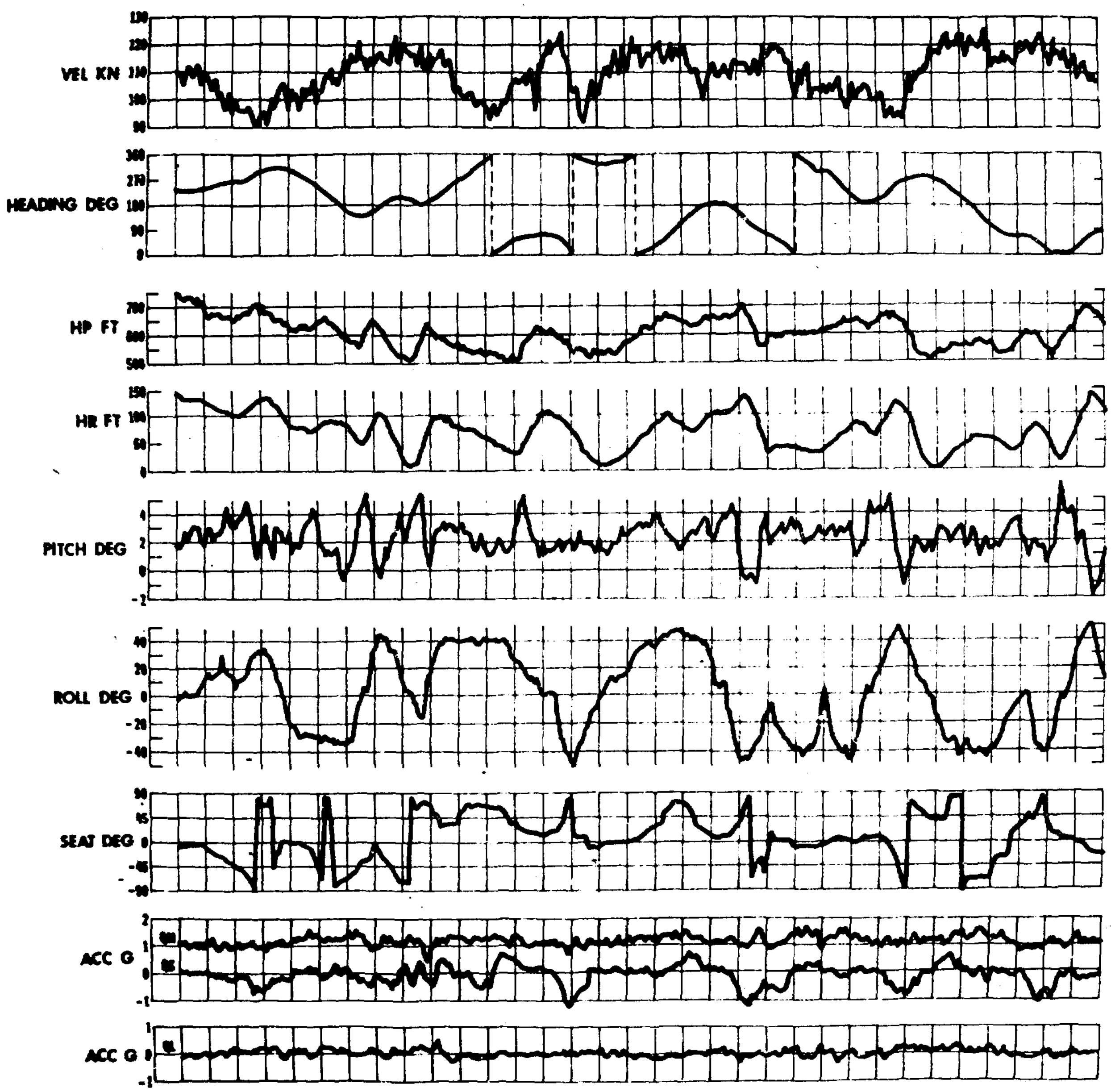

FIGURE 10. Helicopter Flight Profile

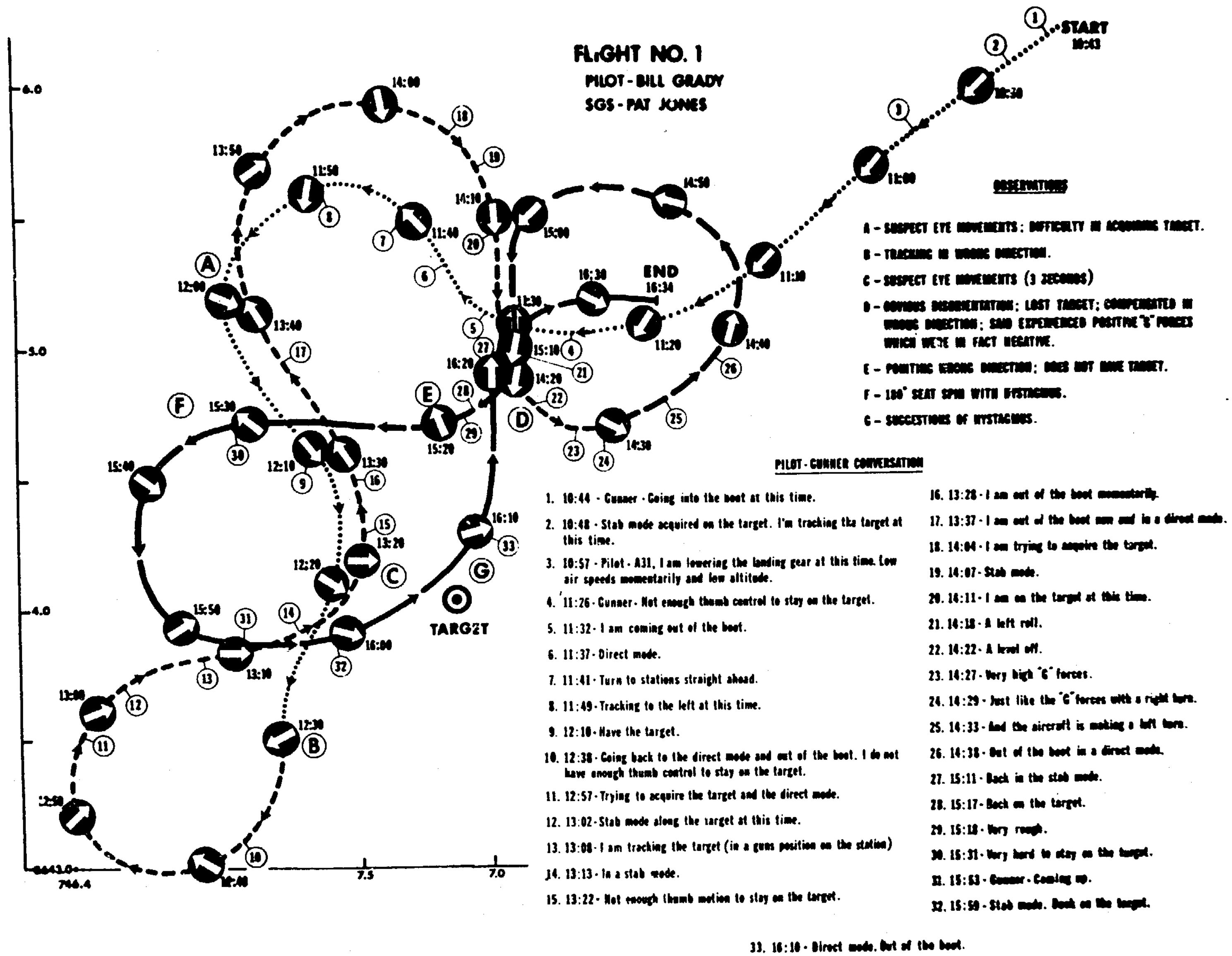

FIGURE 11. Crewman Performance Observation

initial data points and letting the transfer function transients stabilize for 60 seconds; then introducing the rest of the input data points in sequence.

Seat Movement Alone - For this computer run, the helicopter was maintained stationary and the rotating seat with crewman was allowed to follow the actual profile utilized during the flight. The crewman also maintained throughout the profile a 45° forward head tilt. This separate analysis allowed making some judgment as to what part of the effects could be contributed to the rotating seat alone.

Figure 12 is a plot of the nystagmus as predicted by the math model for the given input seat angle changes. It should also be stated again that the vestibular system (semicircular canals in this case) senses only angular acceleration; therefore, the second derivative of the seat angle shown in the figure was the actual input to the system. But, in general, it is possible to correlate and discuss the results (nystagmus) related to seat angle changes as shown on the figure.

As a result of an analysis of Figure 11, it can be concluded that at almost every point identified as a problem area (A,B,C, etc.), the math model predicted significant nystagmus rates to occur except for point E. Two other time periods, 11:30 min and 14:00 min, were also predicted by the computer to be potential problem time periods. In the first case it was noted that the crewman was having problems acquiring the target, but in the second case he was out of the boot and did not report any problems. Point E, which was not accounted for by the seat movements, will be addressed later when the helicopter movements and the seat plus helicopter movements are analyzed. Each of the specific problem areas detailed in Figure 11 will not be totally accounted for in this section but also must await for the composite seat plus helicopter movements analysis. This analysis allows the conclusion to be made that seat angle changes are major contributors to the observed effects.

Helicopter Movement Alone - For this computer run, the crewman was oriented in the helicopter such that he faced in the direction of travel and had his head tilted 45° forward. The resulting nystagmus effects as predicted by the math model are given in Figure 13. It is noted that the specific points representing the problem areas given in Figure 11 do not necessarily coincide with the helicopter induced significant periods of nystagmus as predicted by the math model. However, it can be concluded that the helicopter flight profile followed herein does introduce significant nystagmus effects on a crewman oriented as described above. These effects, in themselves, would probably reduce or hamper the performance capabilities of a crewman and when cross coupled with seat angle changes are even more significant influences.

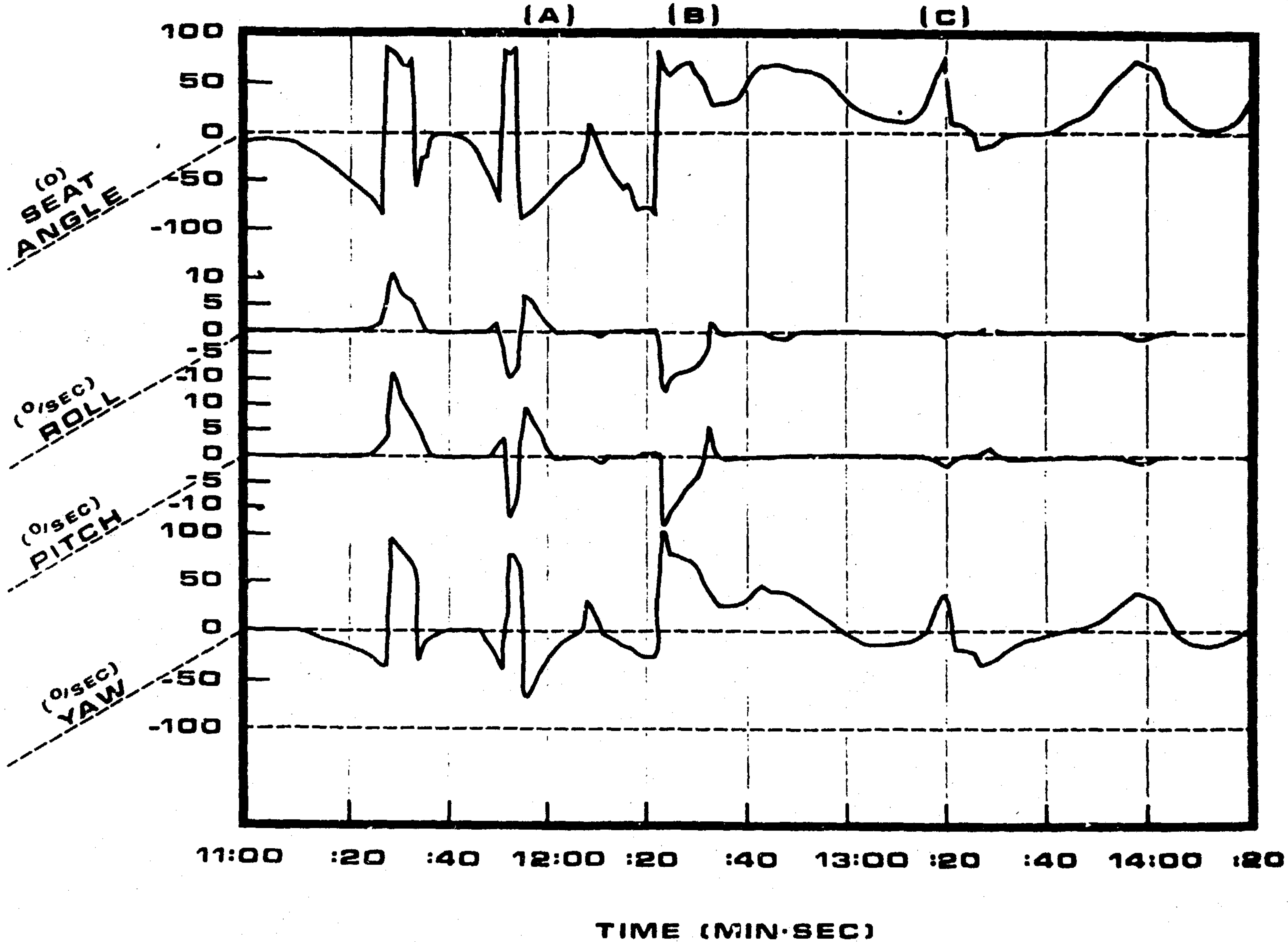

FIGURE 12. Crewman Nystagmus from Seat Angle Changes

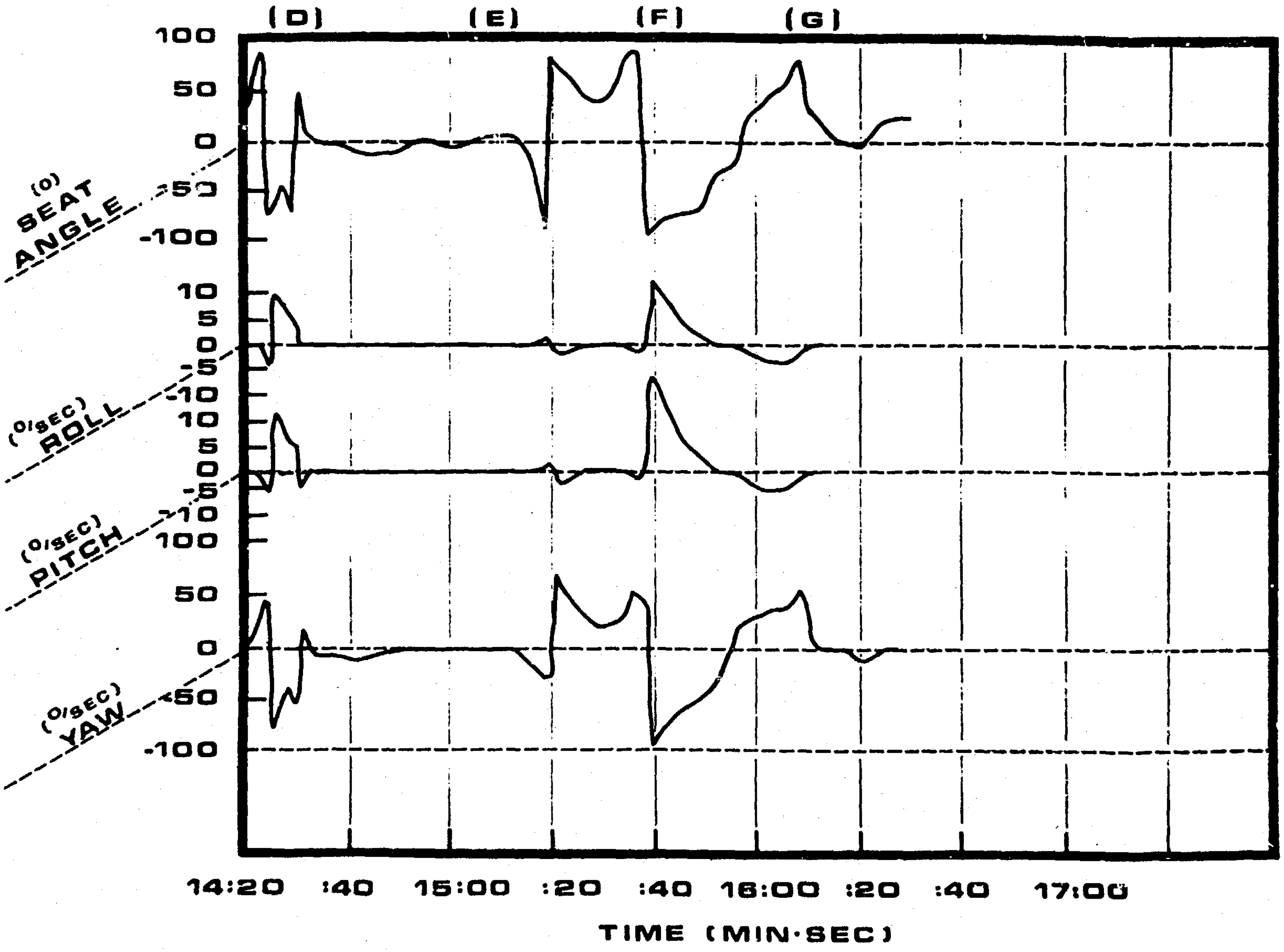

FIGURE 12. Crewman Nystagmus From Seat Angle Changes (continued)

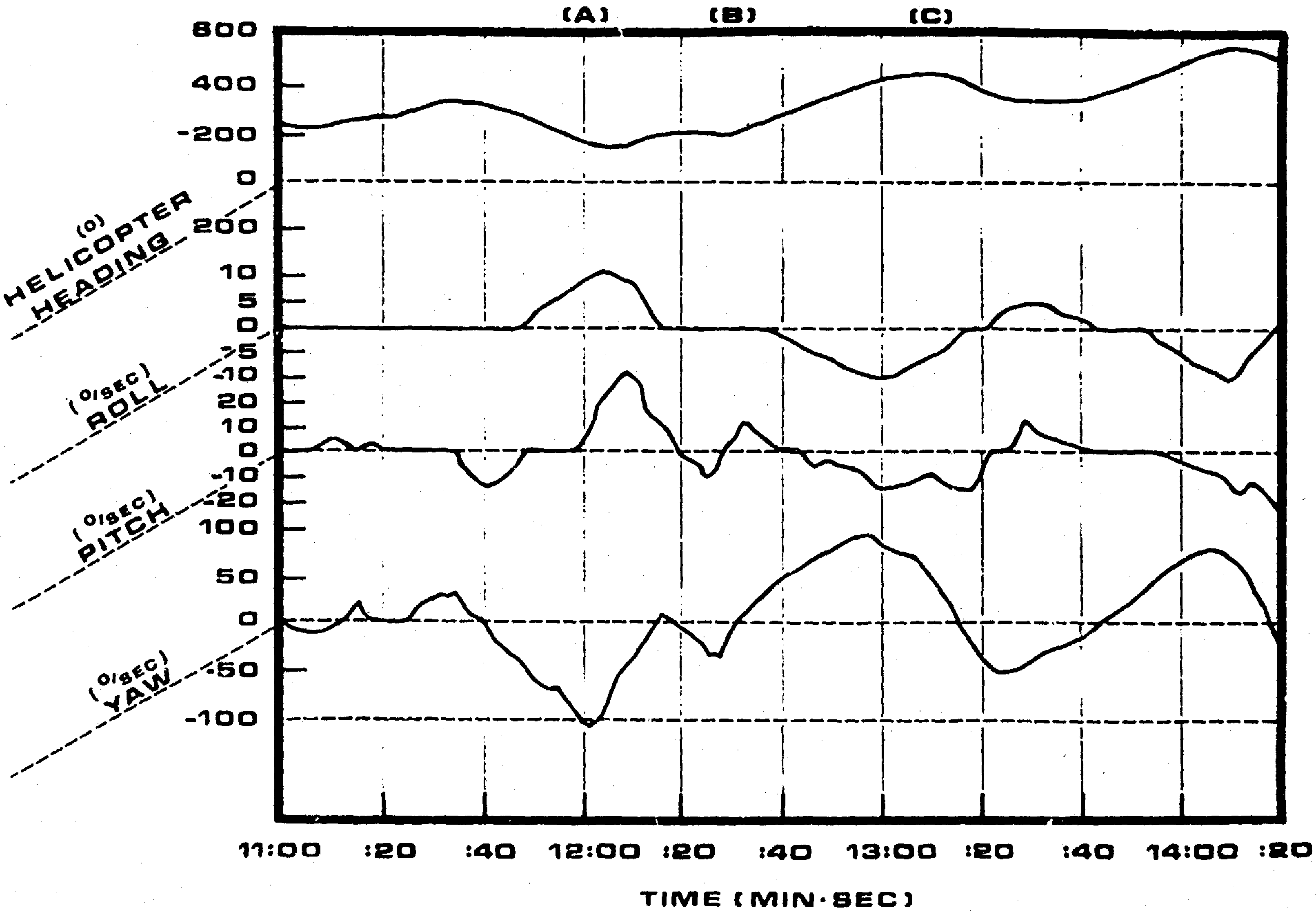

FIGURE 13. Crewman Nystagmus Resulting from Helicopter Flight

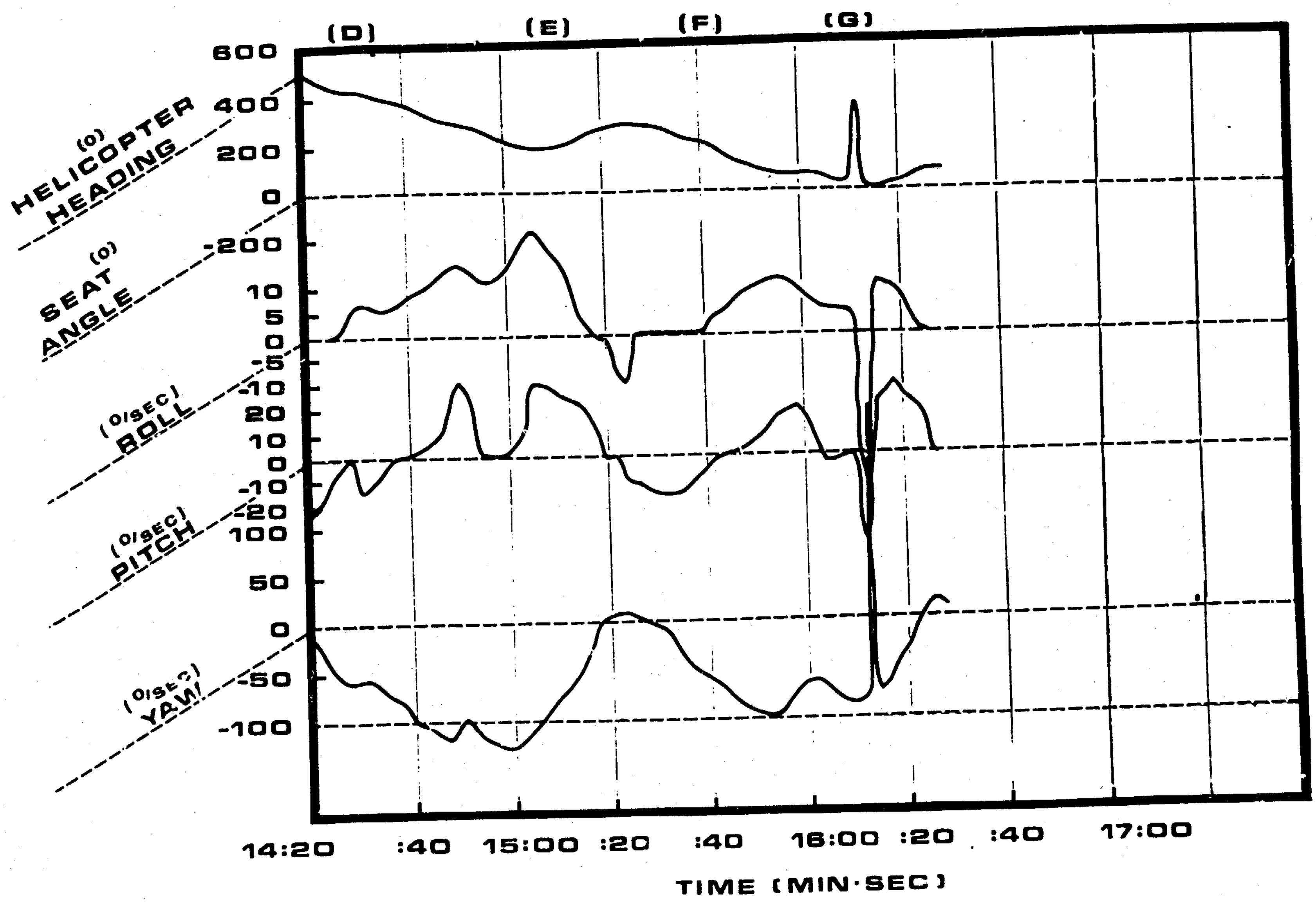

FIGURE 13. Crewman Nystagmus Resulting from Helicopter Flight (continued)

Figure 13, unfortunately, does not show the roll attitude of the helicopter that is occurring simultaneously with the change in heading. The cross-coupling of attitude changes (second derivatives to produce accelerations) is actually what is causing the nystagmus effects (coriolis type illusions). Therefore, in studying Figure 13, one should attempt to correlate the resulting effects to the crewman with heading changes only.

Helicopter Plus Seat Angle Changes - This computer run had the crewman oriented with head tilted 45° forward while the helicopter and seat angle was allowed to change according to the flight profile given in Figure 10. Figure 14 gives the crewman nystagmus effects and Figure 15 gives the crewman perceived sensations of angular motion as predicted by the math model. For this portion of the analysis, both of these results will be utilized in an attempt to correlate what the crewman sees and what he senses.

A few words should first be said in regard to the value of the effects predicted in Figures 14 and 15. It is recalled from the above discussion that the model fitted experimental nystagmus data with good confidence but for perceived sensations did not. Therefore, the nystagmus results will be utilized herein as a primary indication of the effects to the crewman, and perceived sensations will only be utilized in a secondary or support sense. Also, the results as predicted are in actuality an expression of the components making up a coriolis illusion while those predicted in Figure 12 resulting from seat angle changes alone are components of an oculogyral illusion. Nystagmus, as predicted by the math model in general, are those magnitudes of eye movement that would occur in an experimental situation, while during a field test other factors such as concentration on a target (direct cerebral control of the eye muscles) may modify the actual results. Therefore, magnitudes of nystagmus as given in Figure 14 may be higher than actual in some cases but, in general, will still allow one to make a quantitative judgment of time periods that may be considered as problem areas.

Since the crewman controlled the seat angle change in response to environmental effects what is given as a seat angle change profile cannot be in total considered as an input to him initiated by the problems observed. For, in most cases, problems occurred first; then he responded by making seat angle changes to compensate. So, in attempting to analyze the predicted data with those actual results observed in Figure 11, those considerations must be of primary concern.

Separate analysis for each problem area identified follows:

Point A: Suspect Eye Movements: Difficulty in Acquiring Target - This problem occurred at 12:00 min and from Figure 14 a large nystagmus

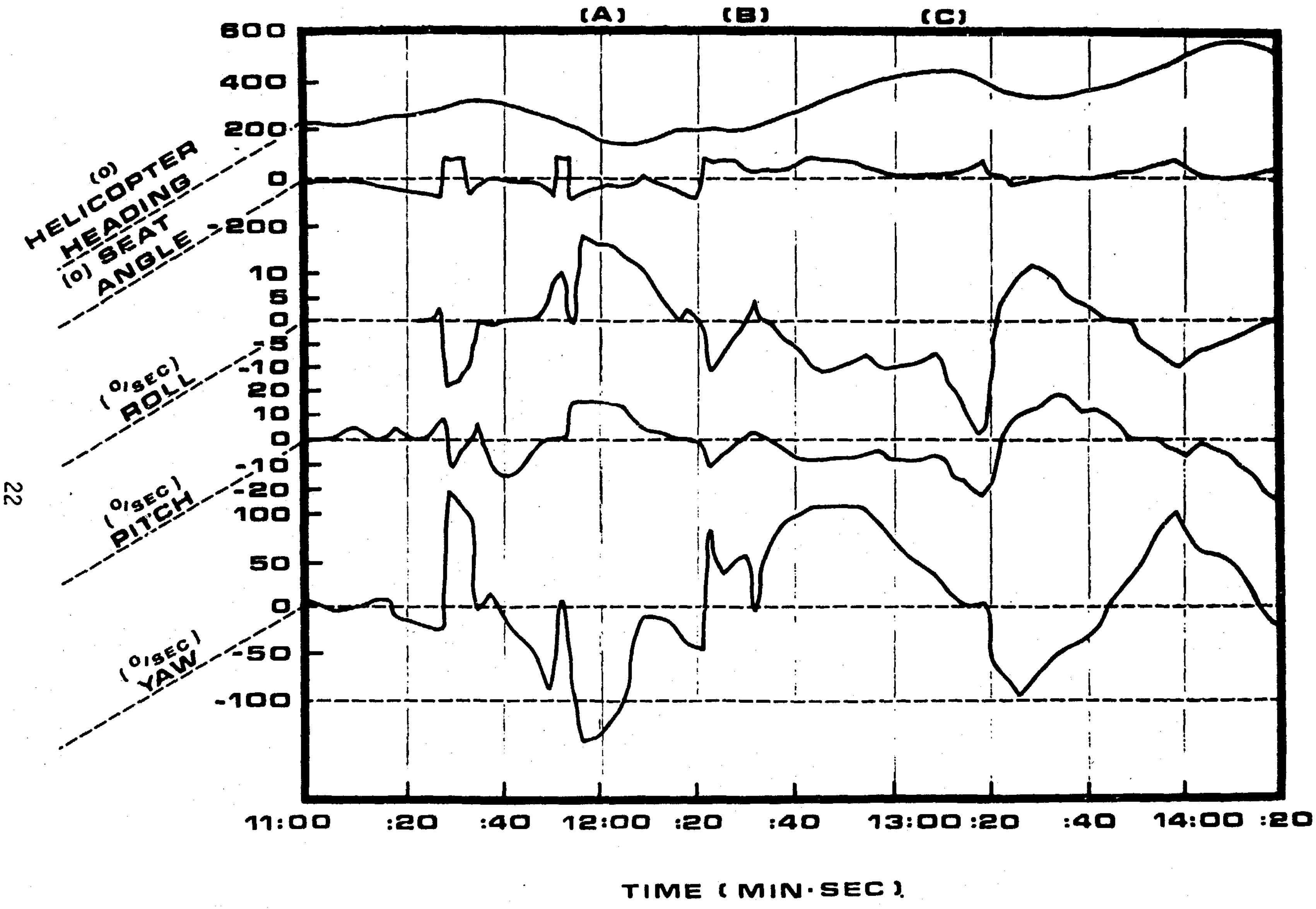

FIGURE 14. Crewman Nystagmus Resulting from Helicopter and Seat Angle Changes

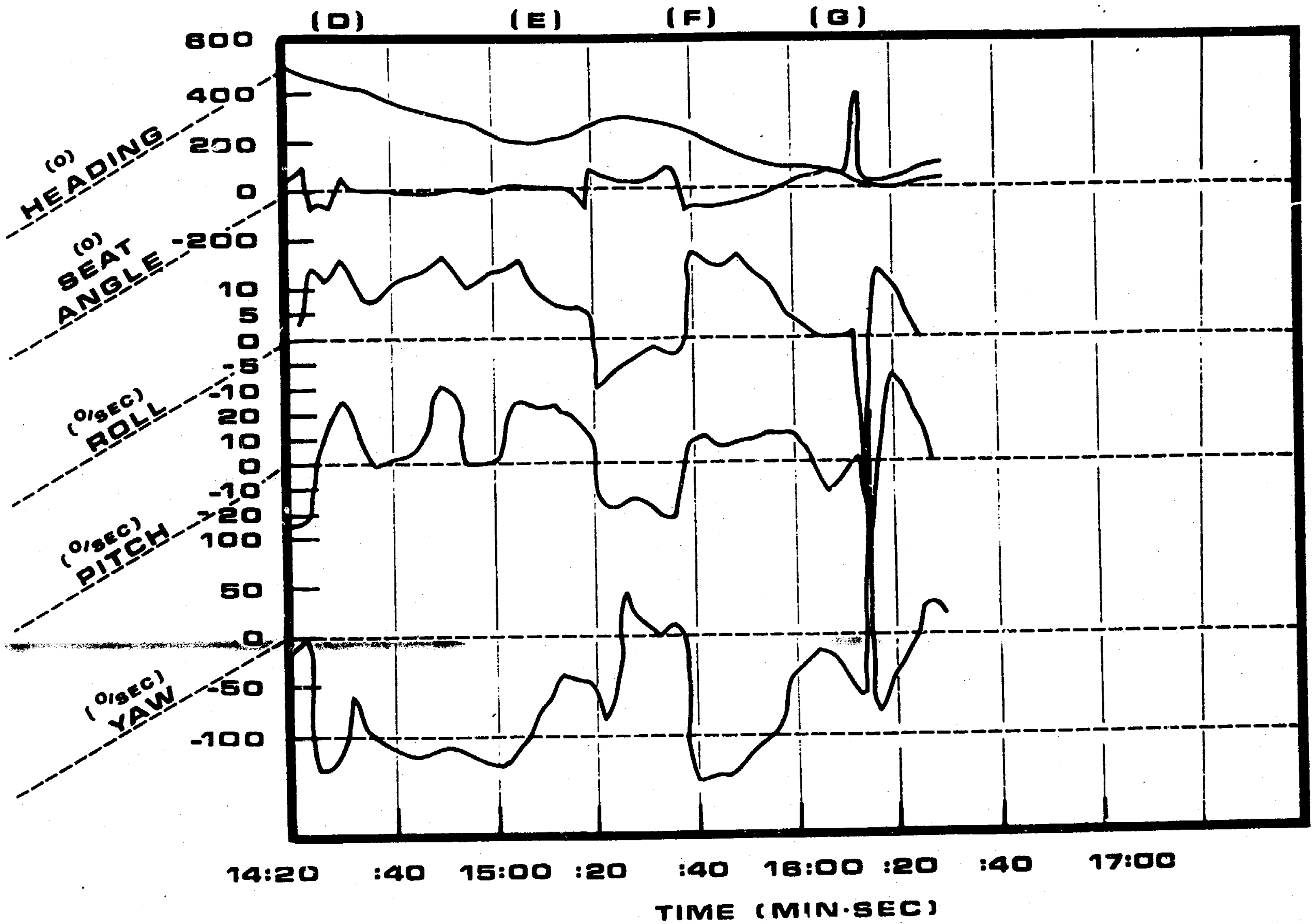

FIGURE 14. Crewman Nystagmus Resulting from Helicopter and Seat Angle Changes (continued)

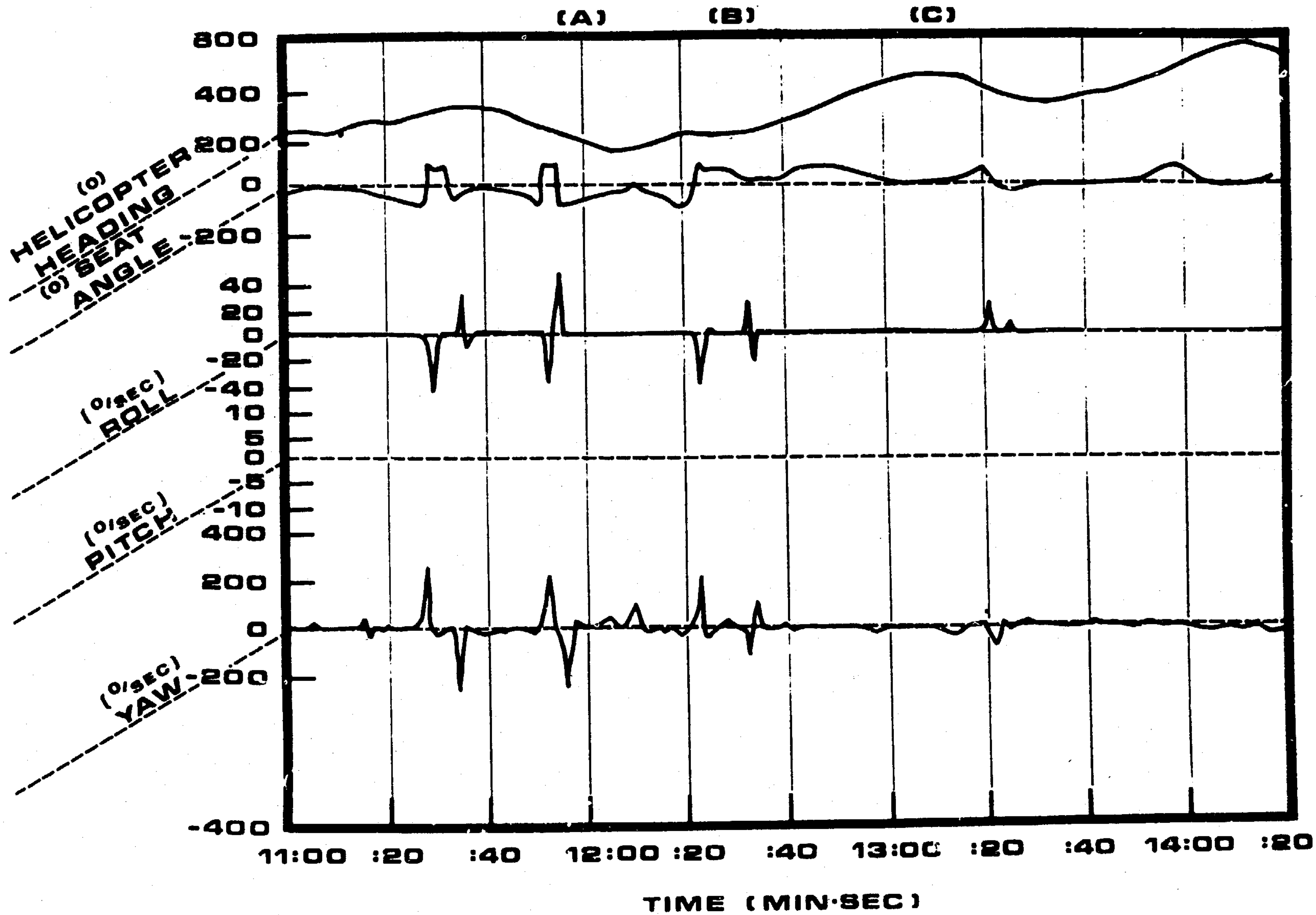

FIGURE 15. Crewman Perceived Motion Resulting from Helicopter and Seat Angle Changes

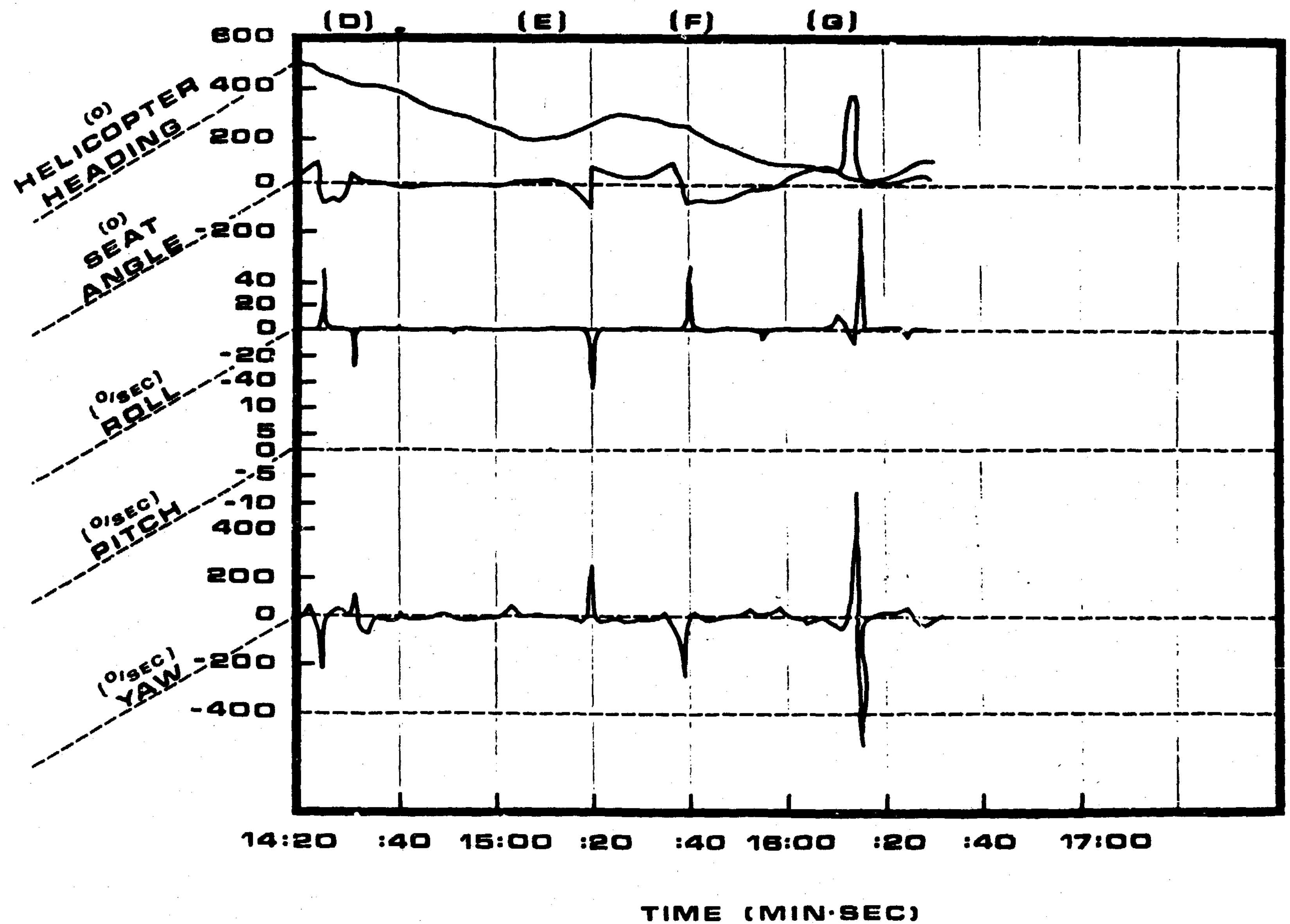

FIGURE 15. Crewman Perceived Motion Resulting from Helicopter and Seat Angle Changes (continued)

(yaw, roll, and pitch components) effect or coriolis illusion is reported. Of course, concentrated tracking of the target by the crewman would modify those effects to some degree but due to their magnitude, difficulty in tracking the target would still probably result. Several large seat angle changes preceded this observation and were no doubt key factors in the resulting effects. At 12:10 min, however, nystagmus effects were greatly reduced and here acquired the target. The perceived sensations during this time duration were large but short in duration; therefore, a confusion between what the crewman saw and felt is not apparent from the data. This is also supported by the recorded observation.

<u>Point B: Tracking in the Wrong Direction</u> - This problem was observed to have occurred at approximately 12:30 min. During this time period, several large seat angle changes were initiated by the crewman, resulting in not only significant nystagmus effects but also in large rapidly changing directions in perceived body motion. The combination of the rolling and yawing simultaneously plus observing a changing visual field may have caused the crewman to experience a confused state during the tracking task, resulting in a complete reversal in his orientation relative to tracking the target. This is, of course, in some regards, speculation because part of the seat angle changes was probably made as a result of environmental influences. Hence, it is difficult to separate normal tracking seat angle changes from those reactions to the environmental influences and resulting states of confusion or disorientation. It can only be concluded from the math model results that during this time period, disorientation was highly probable. At 12:38, the math model again predicts a building up of nystagmus, and it is noted from the observations that the crewman was having trouble in tracking the target and came out of the boot. At this latter time period, perceived sensations were also minimized, with disorientation effects also probably reduced to insignificant.

<u>Point C: Suspect Eye Movements (3 seconds)</u> - This problem was observed to have occurred at approximately 13:20 min. During this time period, nystagmus effects as predicted by the math model were significant and support the observation made. At this time, the crewman again initiated some seat angle changes thereby causing nystagmus and perceived sensation effects to build up. Then at 13:22 min the crewman reported trouble in tracking the target and subsequently came out of the boot. During this time period, large nystagmus effects were predicted by the math model as shown in Figure 14. Perceived sensations were small; therefore, probability of disorientation was not significant and this is supported by the recorded observations.

<u>Point D: Obvious Disorientation; Lost Target; Compensation in Wrong Direction; Said Experienced Positive "G" Forces Which Were, In Fact,</u>

Negative - This problem was observed to have occurred at approximately 14:20 min. Just prior to this time period, roll and yaw nystagmus rates were becoming insignificant but pitch nystagmus (negative) was building; then with a rapid seat angle change in attempting to reacquire the target, rapid yaw and roll nystagmus were produced and pitch rapidly changed directions. Therefore, a changing visual field was probably observed, hence, disorienting the crewman. This, of course, caused the crewman to lose the target. As a result, at 14:26 min (approximately) he then compensated in the wrong direction. During this time frame, the helicopter was also maneuvering rapidly (yaw plus roll) and was probably the major contributor of significant effects to the crewman as observed in Figure 13. Eventually, the crewman had to come out of the boot at 14:38 min.

Unfortunately, the math model utilized in this program only investigated rotational movements; therefore, no detailed conclusion can be made about the linear forces or movements experienced by the crewman. However, seat angle changes were minimal and the helicopter, as commented above, was undergoing rapid flight path maneuvers which resulted in large continuing nystagmus influences. Therefore, a general comment about linear changes during this time period can be made. The conclusion drawn is that these forces were in most probability as significant as observed, i.e., at 14:24 min it was reported "very high G forces."

Point E: Pointing Wrong Direction; Does Not Have Target - This problem was observed to have occurred at approximately 15:20 min. The crewman reentered the boot at 15:11 min, at which time the helicopter movements alone (See Figure 13) would have caused significant nystagmus effects (yaw, roll and pitch) impacting his ability to track a target. At 15:17 min, he reported "Back on the target." Then at 15:20 min, he reoriented the seat 180°, thereby pointing opposite from the target. Between the time periods 15:00-15:20 mins., the crewman perceived a yaw rate which when integrated could have led him to believe that he had physically rotated through a yaw angle for which he then tried to compensate by rotating the seat.

It is also during this time period that pitch nystagmus has the greatest frequency of occurrence. Some experimenters contribute pitch motions as the most apt to cause disorientation and feelings of malaise. At 15:31 min, the crewman expressed "Very hard to stay on target," at which time significant yaw, roll, and especially pitch nystagmus were predicted to be present. Therefore, it can be concluded that between 15:11-15:31 mins., when the crewman was having tracking problems and periods of disorientation, they were in probability resulting from the significant roll, yaw, and pitch nystagmus effects predicted by the math model.

Point F: 180° Seat Spin with Nystagmus - This problem was observed to have occurred at approximately 15:40 min. As noted in Figure 14, large roll, yaw, and pitch nystagmus effects were predicted at this time period. The major cause of these effects can be concluded as due to the seat angle change as noted from Figure 12. Helicopter motion is also a contributor but to a lesser extent than the seat. It should also be noted from Figure 14 that the observed nystagmus was not only large in magnitude but did not decay for a significant time period. This may be why at 15:53 min, the crewman again chose to abandon the task.

Point G: Suggestions of Nystagmus - This problem was observed to have occurred at approximately 16:05 min. At 15:59 min the crewman reentered the boot. The nystagmus effects as shown in Figure 14 are the effects for a crewman continuously oriented with head tilted 45° forward; therefore, in actuality, the effects would be larger than those shown because the crewman would receive an additional input from the head tilt movement. Therefore, it can be concluded that during this time period, the crewman in all probability did exhibit some suggestions of nystagmus.

CONCLUSIONS

The conclusions that can be derived from this analysis are:

The math model for the vestibular system was able to predict periods of potential disorientation which agreed with those observed during the actual flight. The magnitudes of the predicted nystagmus which were based on experimental data, however, were not able to be correlated with actual magnitudes obtained during the flight. Therefore, the value of the model as a quantitative tool has not been completely verified. The perceived motion portion of the model if further optimized with experimental data, would also improve the value of the model.

The rapid changes in seat angle were found to be major contributors to crewman disorientation. Although only a crewman with a forward head tilt angle of 45° was considered, it is believed that this head orientation during task conduction is not the most desirable. At this head position, the yaw semicircular canal is nearly maximally stimulated for a given input. Other head angles should also be investigated.

Helicopter flight attitude changes were found to be contributors to crewman disorientation with the forward head tilt angle, but only in a secondary sense. Their major influence became apparent when cross-coupling occurred between the helicopter and seat angle changes.

Linear effects were not investigated herein, but may have influenced the problems observed in flight. A further study incorporating otolith influences should be performed.

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